Jet Propulsion Laboratory
California Institute of Technology

Probe Technologies

Kim Reh, John Elliott

International Planetary Probe Workshop Short Course on the Ice Giants

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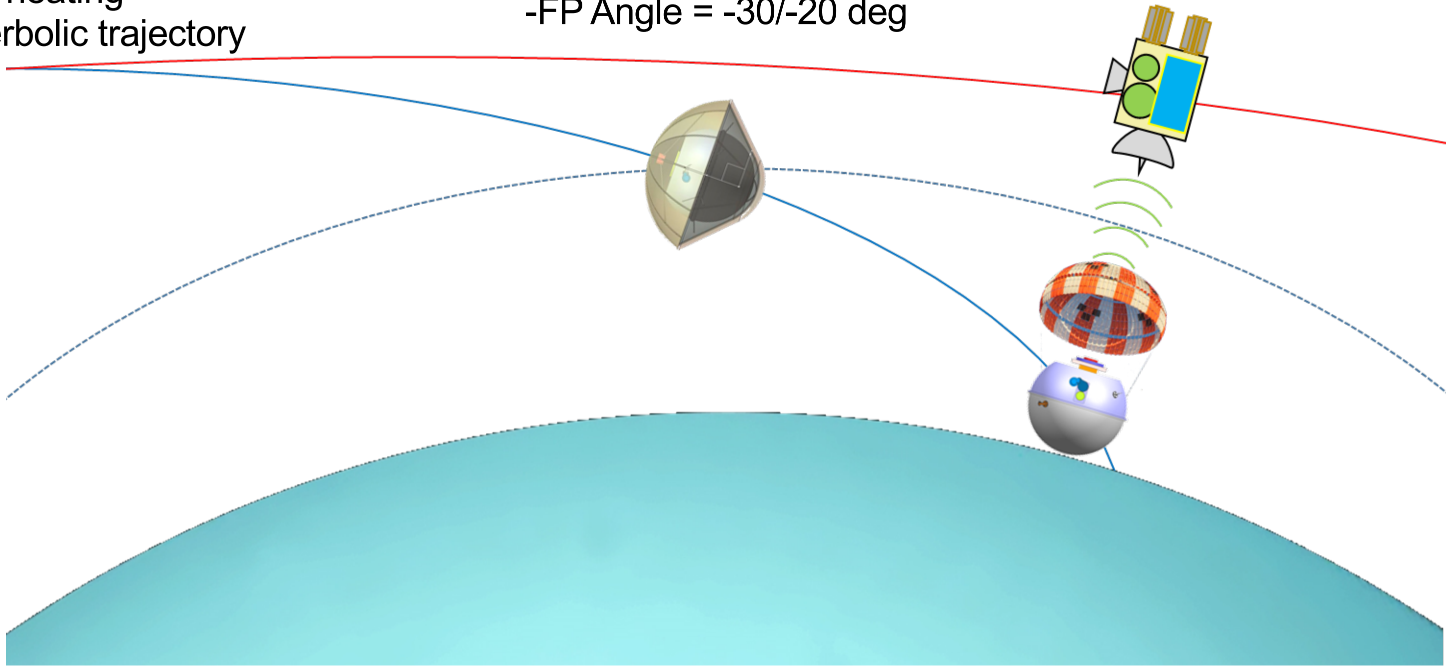
Atmospheric probes are key to Ice Giant origins

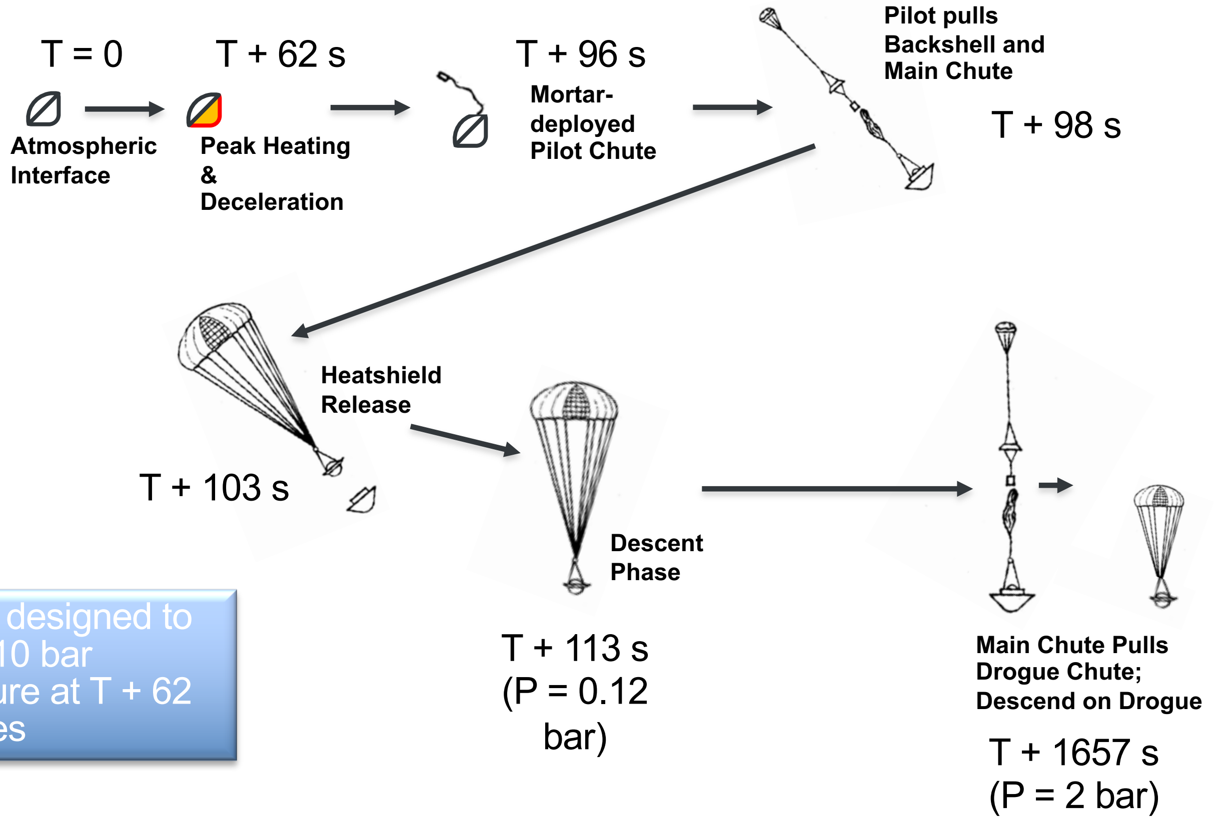
Release:
-60 days prior to entry
-Spin stable
-RHU heating
-Hyperbolic trajectory

Entry (Uranus/Neptune):
-Entry V = 23.5/24.1 km/s
-FP Angle = -30/-20 deg

Crosslink to Orbiter:
-Duration: ~1 hr
-Max Range: <100k km
-Data up: ~15 Mbit



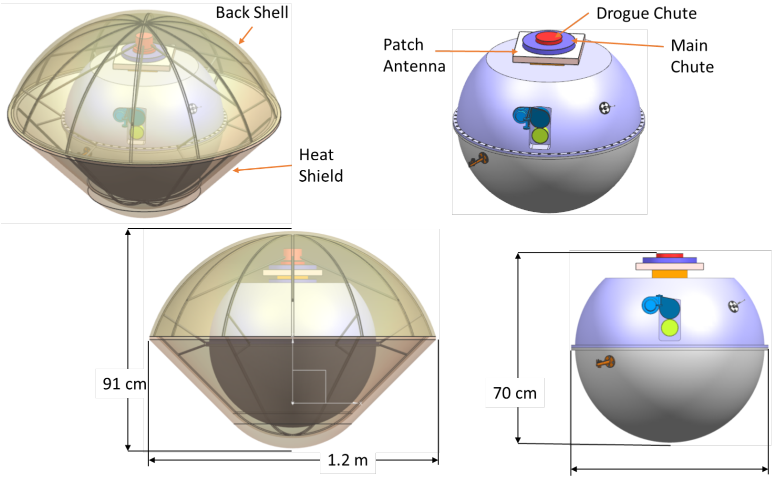
We know how to fly them (Uranus Example)



Probe designed to meet 10 bar pressure at T + 62 minutes

Current probe designs based on SOA instruments and Galileo design heritage

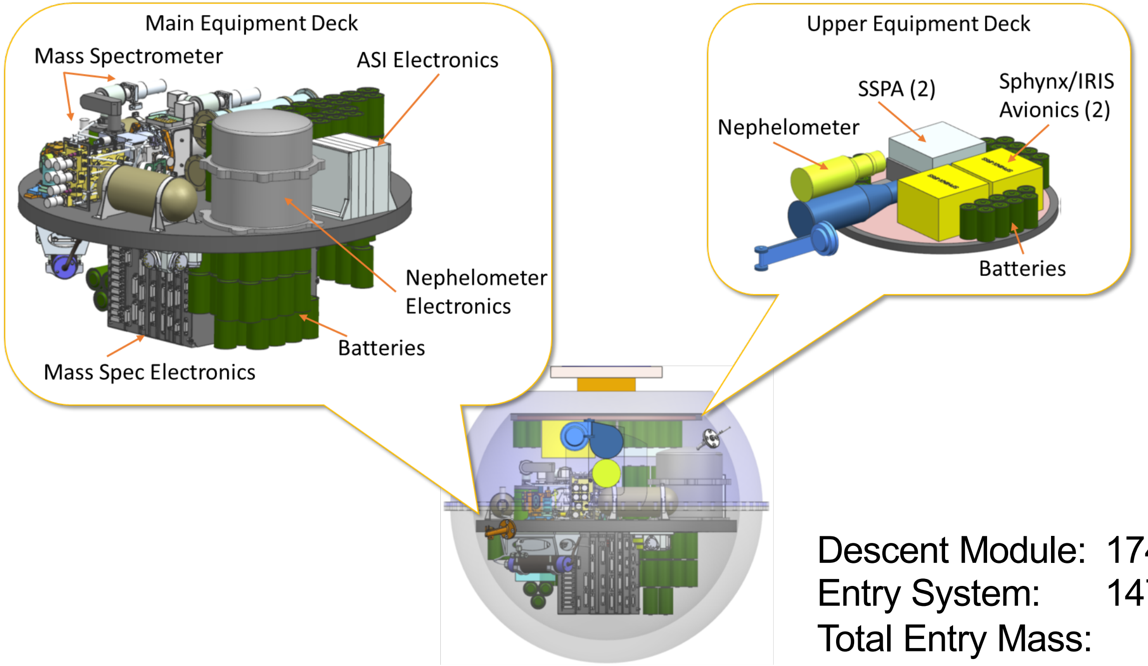
Common probe design for Uranus and Neptune



- Instruments
  - Mass Spectrometer (MS)
  - Atmospheric Structure Instrument (ASI)
  - Nephelometer
  - Ortho-para Hydrogen Measurement Instrument

- CDS
  - Redundant Sphinx Avionics
- Power
  - Primary batteries
    - 17.1kg, 1.0 kW-hr EOM
  - Redundant Power Electronics
- Thermal
  - RHU heating, passive cooling
  - Vented probe design
  - Thermally isolating struts
- Telecom
  - Redundant IRIS radio
  - UHF SSPA
  - UHF Low Gain Antenna (similar to MSL)
- Structures
  - ~50kg Heatshield
    - 45deg sphere cone
  - ~15kg Backshell
  - ~10kg Parachutes
  - ~15kg Probe Aerofairing

SOA drives probe sizing



Descent Module: 174 kg
Entry System: 147 kg
Total Entry Mass: 321 kg

Masses include 43% contingency

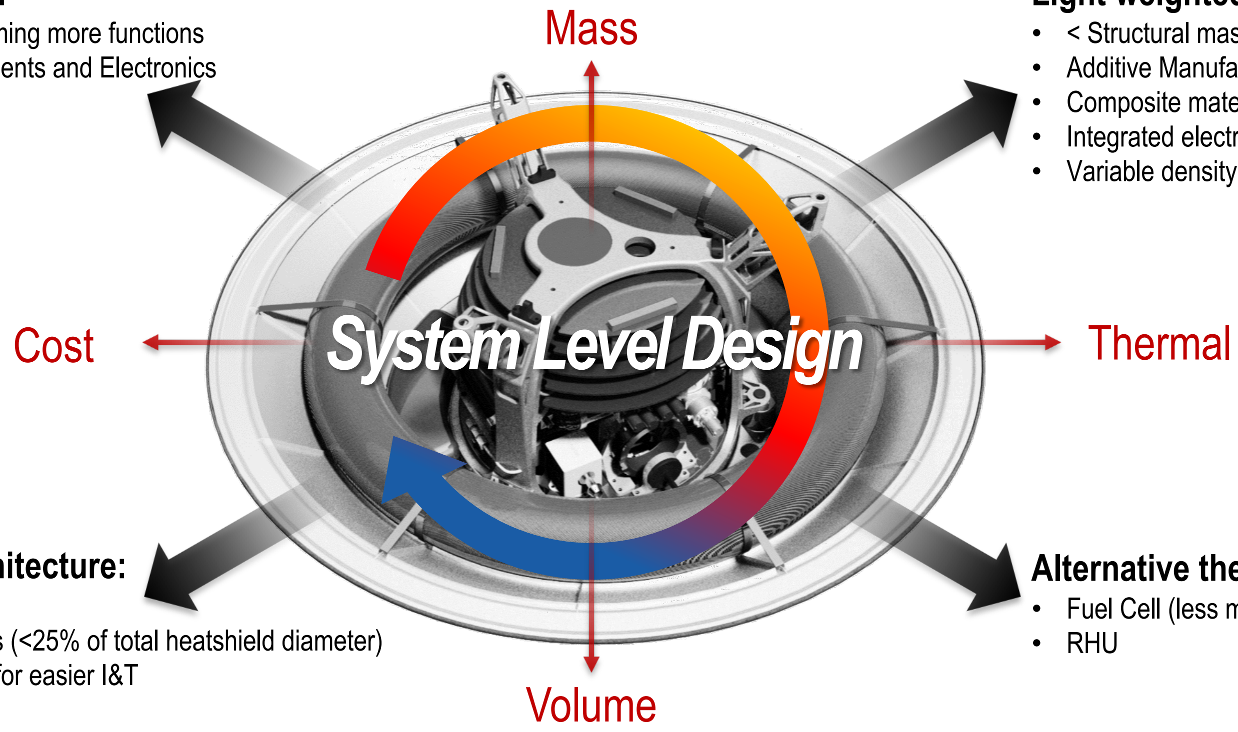
We can do better with infusion of emerging Technologies/Techniques – smaller, more efficient

Multifunctional design

- Fewer components performing more functions
- 3 Modules: Power, Instruments and Electronics
- Lighter integrated aft-shell

Light weighted approach:

- < Structural mass (optimized structures)
- Additive Manufacturing (Titanium)
- Composite material for lower mass
- Integrated electronics (low CG, far from heat)
- Variable density heatshield



Highly integrated architecture:

- Less mass and volume
- Low CG for entry purposes (<25% of total heatshield diameter)
- Single chassis/base plate for easier I&T

Alternative thermal management

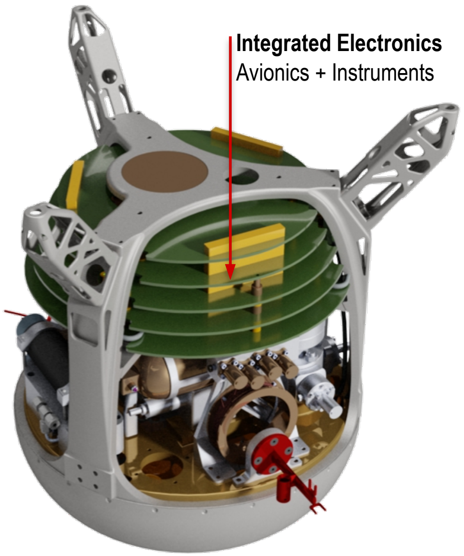
- Fuel Cell (less mass, low CG)
- RHU

Technology Summary: Integrated Electronics

Now **5 Years**

TRL: 6
Heritage:
- Customization of Boards (common practice)
- Stocked connectors (e.g., CubeSats)

Feasibility: Feasible according to JPL experts
Main Risk: Incompatibility of some design
Mitigation: Alternative board design, test board prototypes
Cost: Different shapes do not necessary mean a big extra cost

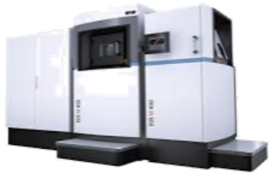


1. Integrated Electronics

Each one of the configurations in the design session used an approach that integrated all of the electronics on to a series of custom fitted and shaped boards located at the top of the probe, in order to minimize the volume of the probe, reduce the CG and locate the more sensitive electronical parts far from the heatshield area. This included all of the electronics for the radio, control systems and the electronics for each of the instruments as well. This is a level of integration that has not been seen on previous spacecraft designs.

Technology Summary: Additive Manufacturing

Now → **5 Years**



TRL: 9 (in Europe)

Heritage:
- Metal 3D printed parts have flown (E.g., Juno)
- Well understood process for titanium
- Statistically bases for material behavior (America makes)

Feasibility:
- Feasible according to JPL experts
- Geometry cannot be implemented with traditional methods (e.g., hollow parts)

Main Risk: Problems design printing, post-process

Mitigation: Easy to build more copies, test on coupons and general structure to assure performance

Cost: Although post-processing is require we assume due to the complexity of the geometry that the final cost is similar to a traditional method with some clear benefits.

2. Additive Manufacturing for Probe Structure

The mechanical structures on the probe were designed to take advantage of modern additive manufacturing techniques. In this way, the structure will be printed in metal as opposed to being fabricated from a single or multiple pieces of solid titanium or aluminum.

Technology Summary: Optimized Structural Design

Now → **5 Years**

TRL: 9 (in Europe)

Heritage:

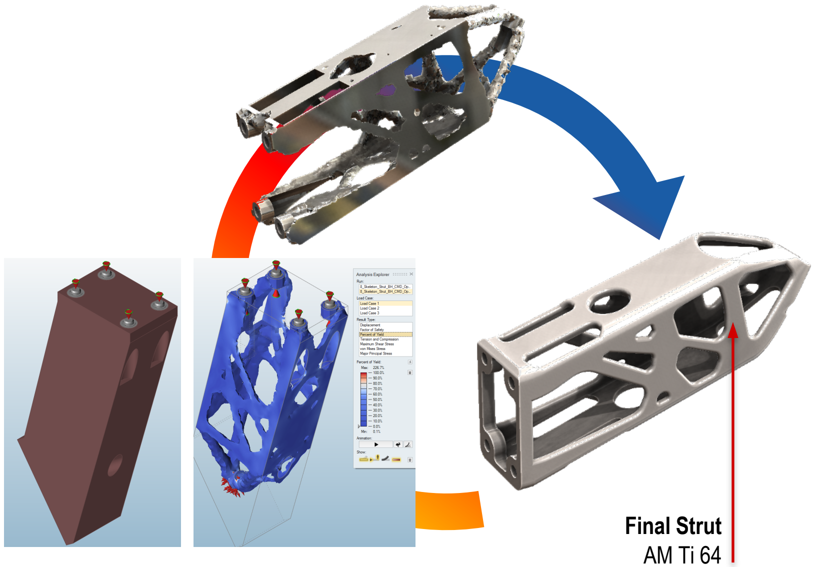
- Metal 3D optimized printed parts are flying already (E.g., ESA Sentinel 1)
- Structural solvers are broadly used in many industries (e.g., Altair solver)

Feasibility: It has been done successfully in other organizations (E.g. ESA)

Main Risk: Issues in the solver and errors in the load conditions

Mitigation: Traditional structure analysis and mechanical tests

Cost: No extra cost beyond software licenses (Around $2k per license)



3. Optimized Structural Design (bone growth algorithm)

In order to minimize the weight while maximizing the strength of the structures in the probe, new methods and software were used as part of the design process. Commercial software (SolidThinking's Inspires) that utilizes a bone growth algorithm to determine the optimal configuration to carry loads given an initial design was used to optimize the structure of the probe.

Technology Summary: Fuel Cells for Cruise Heating

Now → **5 Years**

TRL: 9 for general fuel cell in space, TRL 6 for this approach (?)

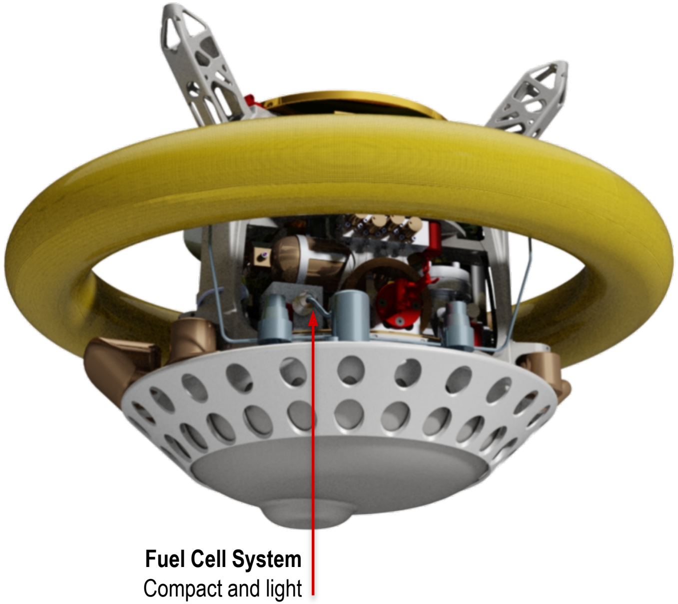
Heritage:
- Fuel systems on ISS
- Apollo program
- http://www.nasa.gov/topics/technology/hydrogen/hydrogen_2009.html

Feasibility:
- Feasible according to JPL experts
- The inefficiency of the system is heat
- It reduces the weight in comparison with batteries with higher energy density

Main Risk: Problems in the design, issues with the release of conductors

Mitigation: Test in space conditions chambers

Cost: This requires more detailed explanation



4. Thermal Regulation by Fuel Cells

An innovative approach to the challenge of thermal management was to rely upon the exothermic property of the reaction between hydrogen and oxygen to create water. Through the use of tanks, oxygen and hydrogen could be stored for release during the cruise stage of the mission for thermal management of the probe and its components.

Technology Summary: Multi-function System Design

Now → **5 Years**

TRL: 3

Heritage:

- Multifunctional design is a general principle applied in many industrial fields

Feasibility:

- Feasible according to JPL experts

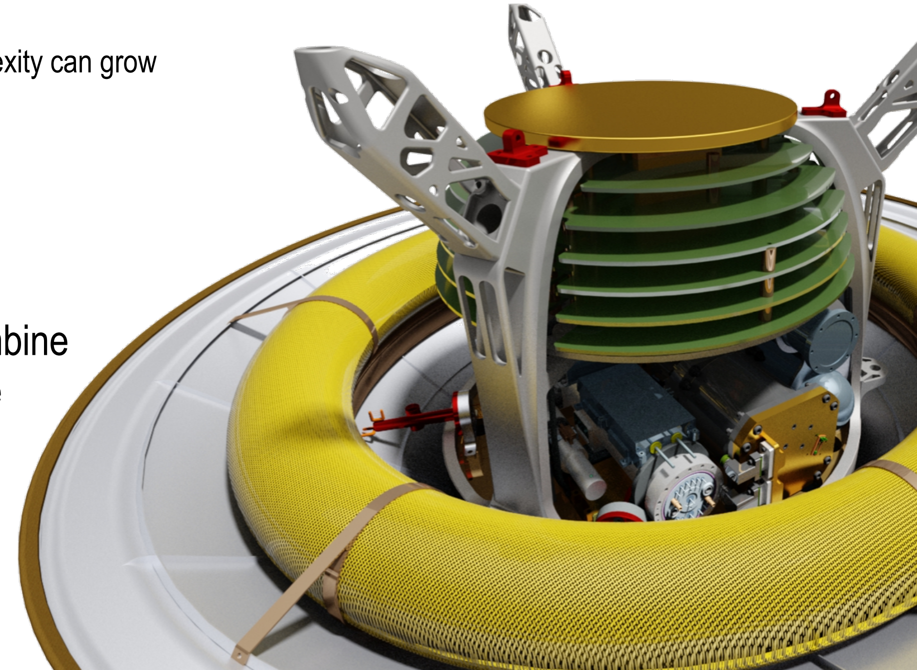
Main Risk: Incapability to combine several functions in one component, complexity can grow

Mitigation: Different design, more components

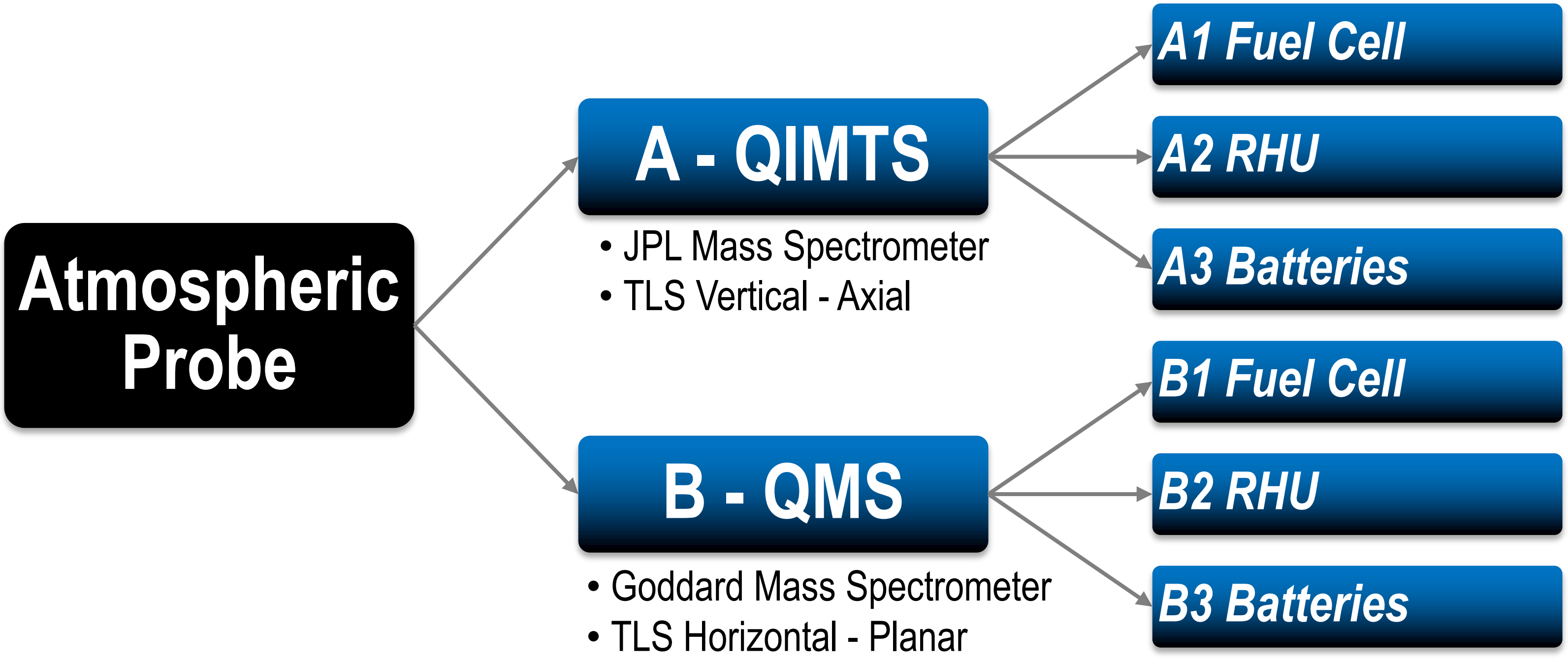
Cost: Potentially this reduces cost (mass, volume)

5. General System Level Design: Multi-functionality principle

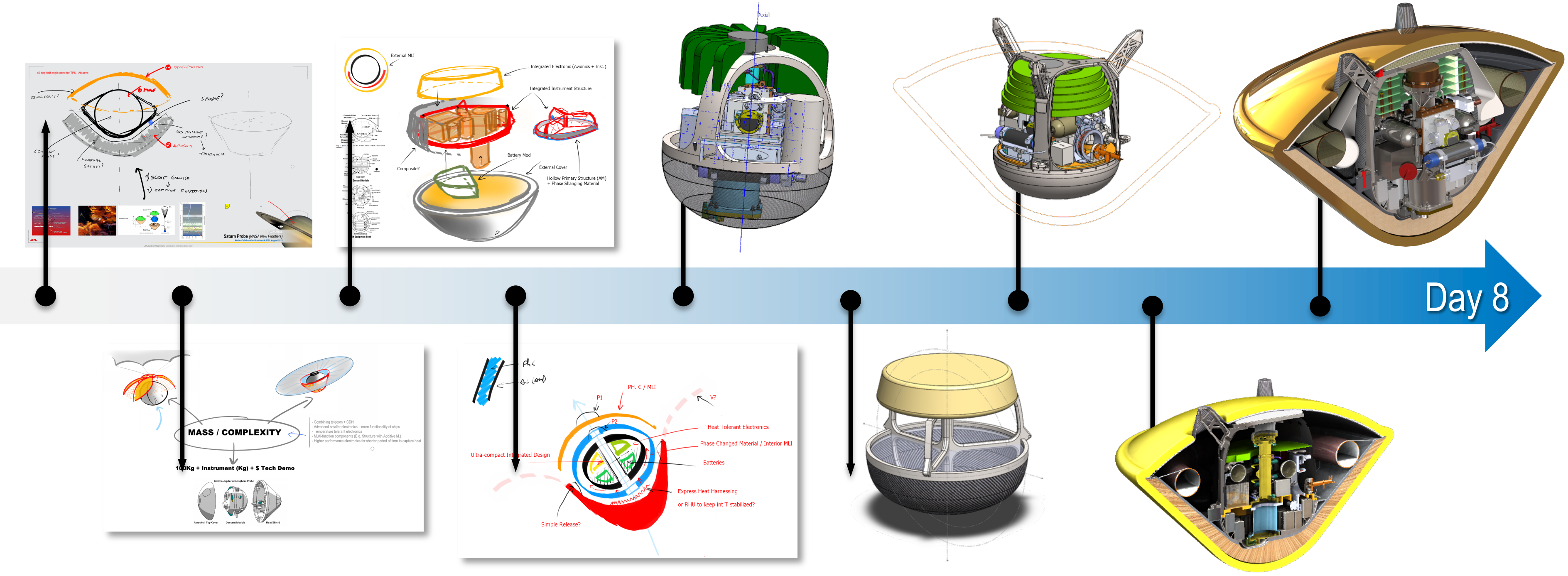
The general design principles behind this concept were to combine as many functions as possible in each component, simplify the integration and manufacturing process and make the probe as compact and light as possible.



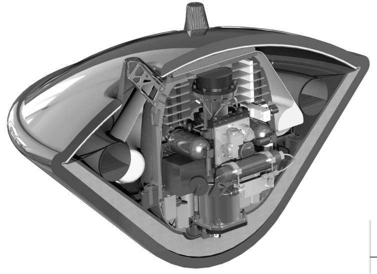
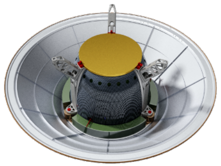
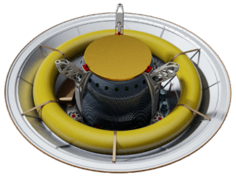
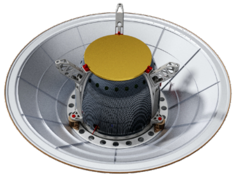
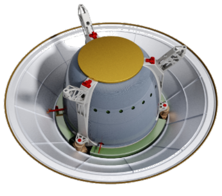
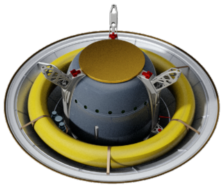
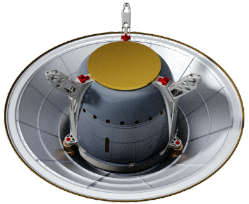
Probe Concepts Considered Two Different MS Designs and Three Options for Coast Thermal Control



Concurrent Design example demonstrates that emerging technologies enable more optimized efficient probe concepts while maintaining aeroshell commonality



Prototype Summary Results Show Significant Reduction of Mass and Size Over Baseline

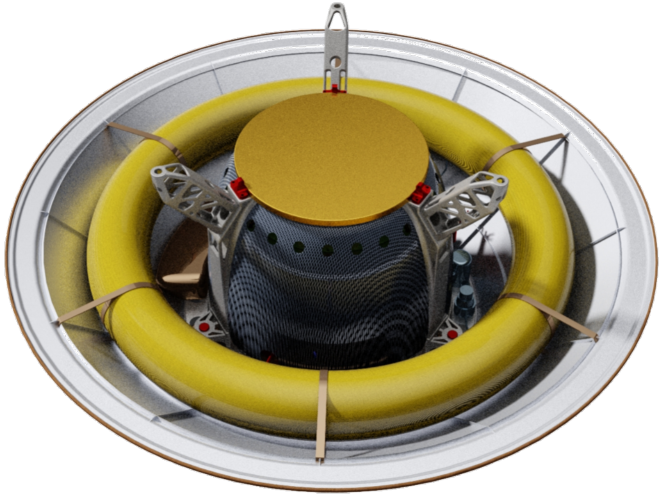
	QITMS (JPL) – TLS Axial						QMS (Goddard) – TSL Planar						Baseline
	Electric		Fuel Cell		RHU		Electric		Fuel Cell		RHU		
MASS (kg) | Difference	Mass (kg)	Difference	Mass (kg)	Difference	Mass (kg)	Difference	Mass (kg)	Difference	Mass (kg)	Difference	Mass (kg)	Difference	Mass (kg)
Current Best Estimate + 43%	185.1	-42.2%	174.8	-45.5%	163.7	-58.9%	202.5	-36.8%	192.2	-40.0%	181.0	-43.5%	320.5
Probe Diameter (m) | Difference	0.36	-50.7%	0.36	-50.7%	0.36	-50.7%	0.43	- 41.1%	0.43	- 41.1%	0.43	- 41.1%	0.73
Heatshield Diameter (m) | Difference	0.9	-25%	0.9	-25%	0.9	-25%	0.9	-25%	0.9	-25%	0.9	-25%	1.2
Relative Cost (% of baseline)		68.5%		80.5%		85.5%		68.5%		81.5%		86.0%	100%
Technology Infusion	Additive Manufacturing / Light Materials Integrated Electronics Optimized Structure		Additive Manufacturing / Light Materials Integrated Electronics Optimized Structure Fuel Cell Thermal management Integrated Toroidal Tanks		Additive Manufacturing / Light Materials Integrated Electronics Optimized Structure RHUs		Additive Manufacturing / Light Materials Integrated Electronics Optimized Structure		Additive Manufacturing / Light Materials Integrated Electronics Optimized Structure Fuel Cell Thermal management Integrated Toroidal Tanks		Additive Manufacturing / Light Materials Integrated Electronics Optimized Structure RHUs		

Conclusions

- Current studies for Ice Giant missions rely on conventional designs dating back to Galileo
- Emerging spacecraft technologies combined with integrated multi-functional system design can lead to substantial reductions in probe mass, volume, and cost
- Miniaturization of probe instruments would bring dramatic benefits
- Technology infusion will enable more architectural choices

Backup

Infusion of new technologies enable breakthrough development of more effective and affordable atmospheric probes for space science investigations

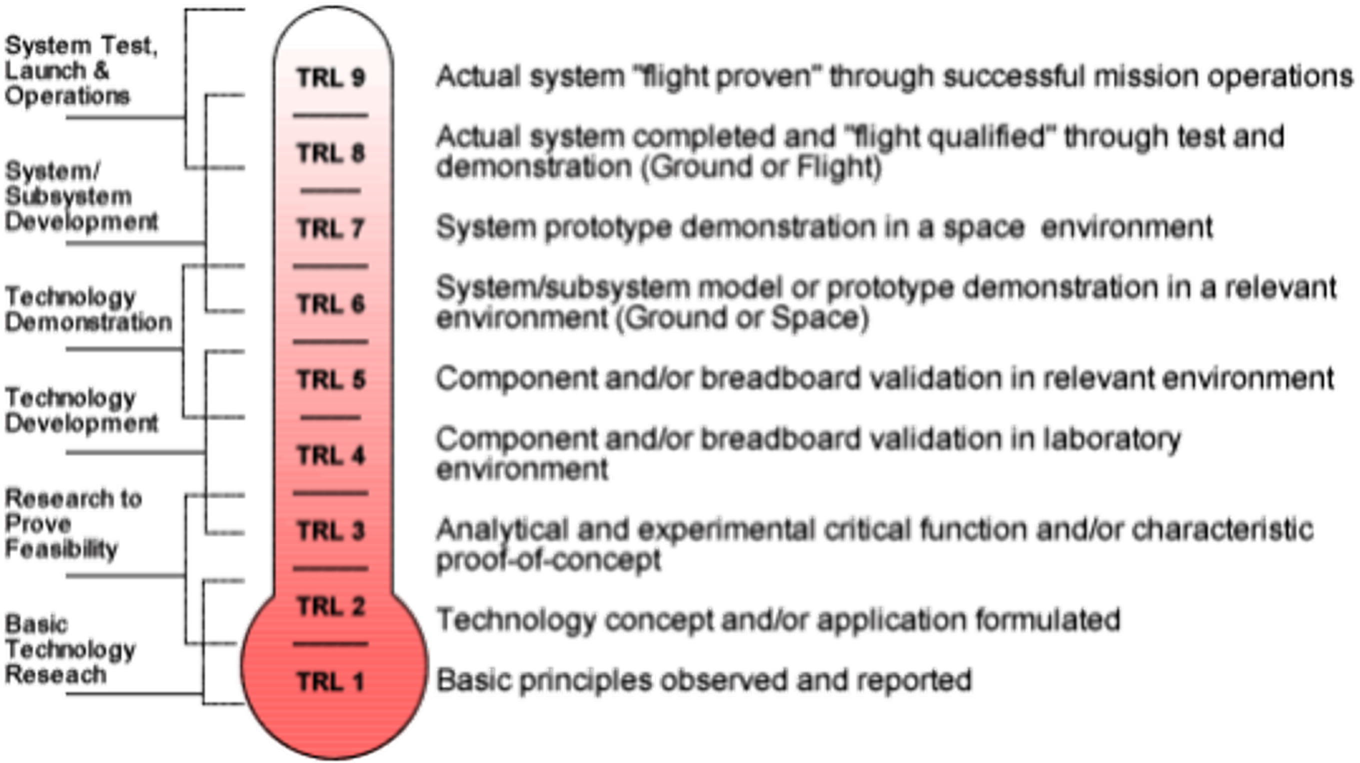


1. Integrated Electronics
2. Additive Manufacturing
3. Optimized Structural Design
4. Fuel Cells for thermal management
5. Multi-functional design paradigm

Emerging Technologies/Techniques can Lead to Smaller and Simpler Probes

- **Highly compact architecture:**
  - Less mass and volume
  - Low CG for entry purposes (<25% of total heatshield diameter)
  - Single chassis/base plate for instrument integration improvement and simplification
- **Extremely light weight architecture:**
  - Less structural mass through the use of optimized structures (load driven geometries)
  - Additive manufacturing techniques (complex geometries) and composite material to further lower mass
  - More compact integration of instrument and avionics electronics (smart mass) far from heatshield while lowering CG and presenting easy access for test and integration
  - Variable density heatshield (using HEEET material)
- **Alternative thermal management architecture:**
  - Fuel cells as the primary heat source during coast to reduce mass and provide extra power
  - Primary Batteries
  - RHUs
- **Integrated multifunctional architecture**
  - Fewer components performing more functions
  - 3 basic modules for easier I&T: Power, Instruments and electronic/structure module
  - Lighter integrated aft-shell , or none

Technology Readiness Levels by NASA Definition




B4 Design Activity
SYSTEM DEFINITION
DETAILED MODELING
RAPID SIMULATIONS
TECHNOLOGY INFUSION
DESIGN STRATEGY
Atelier
SYSTEM LEVEL DESIGN
10 Days - Collocated – Fast Pace
COST AND RISK ASSESMENT
INNOVATIVE ENVIRONMENT
RAPID PROTOTYPES
JPL

Design Maturation and Risk Reduction

2.1 Systems

For systems engineering and system modeling the goal was to produce a parametric description of one of the six configurations in a complete enough manner that it would allow for minimal modifications in order to facilitate the system descriptions of and comparisons to the other five configurations.

2.2 Avionics

Avionics focused mostly on the Command and Data Handling (C&DH) aspect of the design. Specifically the approach was to identify and combine duplicate functionality in the electronics, change the form factor for the electronics to minimize the overall volume of the probe and to ensure that all of the electronics were integrated.

2.3 Mechanical

The mechanical aspect of the probe focused on a minimization of mass and volume for the final design. Segments of the structural design that could serve more than one function were identified and the design was evolved in order to introduce as many dual-use components as possible. In addition, optimization of the structure was used to further minimize mass by eliminating solid structures that provide little or no unnecessary load or stability support.

2.4 Thermal

There were two areas of focus for the thermal design. One was to look for alternative methods to ensure that the probe's components were not damaged due to the low temperatures possible during the cruise phase (although the possibility of a cold cruise was explored). Another aspect was to look at designs that minimized heat loss from within the probe, especially those elements that interface or connect with the cruise vehicle.

2.5 Integration and Test

The use of technologies such as additive manufacturing and integrated electronics pose particular challenges for integration and test. In order to address those concerns, full size 3D printed prototypes of the design were created to verify the feasibility of the design with respect the integration and test activities.

2.6 Cost

In the area of cost analysis and estimation, the primary analogy was the Galileo Jupiter probe. Additional analogous projects based on components of the spacecraft were added to the analysis. In addition, cost and risks associated with additive manufacturing and other innovations were considered, as well as other aspects of the project environment. The cost estimates include the uncertainty of the estimate and a distribution of probable cost.

Now → 5 Years

TRL: 3

Heritage:

- http://ntrs.nasa.gov/search.jsp?R=19730023034
- Gas tanks: http://www.ac.com.pl/en/produkt/373/tytan-gas-toroidal-tank

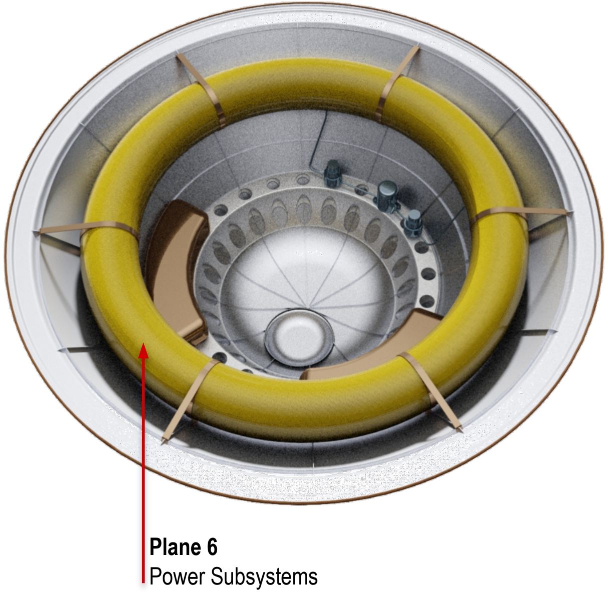
Feasibility:

- Feasible according to JPL experts but work with vendors is required
- Very low pressure for his application
- Material: Aluminum and carbon fiber

Main Risk: Problems design printing, post-process

Mitigation: Easy to build more copies, test on coupons and general structure to assure performance

Cost: Although pros-processing is required we assume due to the complexity of the geometry that the final cost is similar to a traditional method with some clear benefits.



5. Integrated Toroidal Tanks (Fuel Cell)

An innovative approach to address the storage of hydrogen and oxygen for fuels cells for thermal regulation was the use of a toroidal tank integrated with the heat shield of the probe. Driven on the need to minimize the utilization of space while not disturbing the structure or contents of the probe once the heat shield was utilized, the approach of using toroidal tanks integrated in the heat shield served this purpose.

Now → **5 Years**

TRL: 3

Heritage:

- TeamX and Ateam
- Architectural and engineering design environments
- Renaissance workshops
- Autodesk Pier 9
- Frank Gehry Studio
- Etc.

Feasibility:

- Feasible according to JPL experts

Main Risk: Still a new process, overall perspective, depth on technical assessments

Mitigation: More studies, client feedback, tests

Cost: Less than $90K

7. Atelier Process

An integrated approach to concurrent design & engineering, in an accelerated, motivating, fun environment.

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